POWER SYSTEM DISTURBANCES DURING A K-8 GEOMAGNETIC STORM: AUGUST 4, 1972

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ABSTRACT

Solar flares can trigger severe fluctuations in the earth's magnetic field, termed geomagnetic storms. Geomagnetic storms produce quasi-dc currents in 60 Hz electric power systems. These spurious dc currents caused undesirable equipment and system operating effects. A moderately severe geomagnetic storm occurred on August 4, 1972. The effects of that storm on electric power systems in the continental United States and parts of Canada are documented and related to latitude, geological factors, and intensity of the recorded geomagnetic field variations.

INTRODUCTION

A moderately severe geomagnetic storm occurred on August 4 and 5, 1972, caused by a large solar flare of one to two days earlier. The geomagnetic storm produced a large number of minor to major disturbances on electric power systems in the United States and Canada. Because the reliability and security of existing and future power systems can be affected by this phenomena, it is important to document and record all known facts concerning the geomagnetic storm and the associated power system disturbances. With this data, corollary studies can be made with both past and future geomagnetic storms.

Beginning in late 1968, the Edison Electric Institute (EEI) sponsored the Solar Magnetic Disturbances Research Project (RP-85), aimed at investigating the effects of geomagnetic storms on electric power systems.[1,2] The project was a joint effort of the University of Minnesota, the General Electric Company, approximately thirty investor-owned electric utility companies, plus several U.S. Governmental and Canadian electric power organizations. The operating companies and organizations installed recording dc ammeters in the neutral leads of selected grounded-wye power transformers to record the quasi-dc currents caused by the geomagnetic storms; these currents have come to be called solar-induced-currents (SIC). Attempts were then made to correlate these SIC with observed system operating disturbances and equipment effects.

The geomagnetic storm of August 4-5, 1972, was one of the most severe storms of the present cycle of activity, and illustrates well the unpredictability of these events, even in waning portions of the activity cycle.

The power system data presented in this paper was obtained by (1) querying those operating companies and organizations that were participating in the EEI-sponsored research project, and (2) by requesting reports from all companies and organizations through the National Electric Reliability Councils (NERC). All responses that were obtained are included in this paper.

The geomagnetic field data that is presented was obtained from the World Data Center A for Solar-Terrestrial Physics, National Oceanic and Atmospheric Administration (NOAA), Boulder, Colorado.

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THE GEOMAGNETIC STORM

There are a number of indices used to indicate the severity of geomagnetic storms; one which is widely used is the K-index. The K scale is a quasi-logarithmic scale extending from zero to nine, with ± gradations. K-0 indicates no transient fluctuations in the geomagnetic field, whereas a storm of K-9+ would indicate one of the most intense ever recorded. On the K-scale, the storm of August 4-5, 1972, is classed as K-8; this must be qualified, however. A geomagnetic storm classed as K-8 indicates that at one or more of the magnetic observatories in the world, the field variations were of an intensity to be classed as K-8, as compared to the history of recorded field variations at that particular observatory. Thus a K-8 storm is not necessarily of that relative intensity at all magnetic observatories. Consequently, the magnitudes of the geomagnetic field fluctuations are not the same for different geographical areas during a particular storm. This should be kept in mind as the data in this paper is reviewed.

The geomagnetic field disturbance that caused the most pronounced, widespread effects on power systems began at approximately 2242 hours universal time (U.T.), August 4, 1972 (2242 U.T. = 1742 central daylight time). The standard, storm, and rapid-run magnetograms from the various magnetic observatories at 2242 U.T. are disturbed to the point of not being legible. Figure 1 shows the variations in K-level at Fredericksburg, Virginia, for each 3-hour interval during the day, and indicates the varying intensity of the storm. For comparative purposes, the change in field intensity at Boulder, Colorado, at the time of power system disturbances, was 200 gamma. One gamma = 10^{-5} gauss, and 1 gauss = 1 line/cm^2. The steady-state magnitude of the earth's magnetic field at the north and south poles, where it is strongest, is approximately 0.7 gauss.

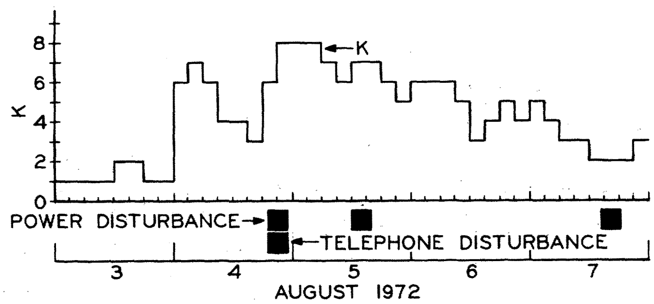

Fig. 1. Fredricksburg, Va. K-Index

SIC RECORDED

For the time period during which the data-gathering phase of the research project was implemented, there were between 60 and 70 SIC recorders on power systems in the U.S. and Canada.[1] By August 4, 1972, nearly all of the SIC recorders had been deactivated, except for those companies that were involved in the transformer-oil gas analysis – SIC correlation program. Figures 2 to 4 show SIC recordings for the time period when the most severe and widespread power system disturbances were noted, i.e., approximately 2242 U.T.

The SIC of Figures 2-4 were recorded in the neutral leads of grounded-wye power transformers. Transformer specifications for each case are given, and ac exciting currents can be compared with the SIC. The SIC in each phase winding can be assumed to be 1/3 of the neutral SIC. Thus, the SIC values indicated are in the range of 10 to 18 times the RMS value of the ac magnetizing current. It is of interest to note that the undulations in the SIC were more rapid in this storm than earlier storms.[1]

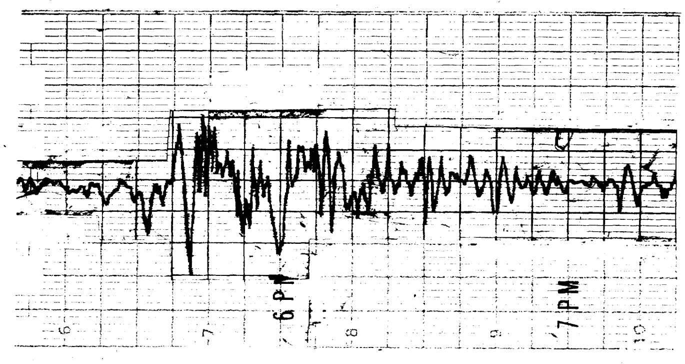

Fig. 2. SIC at Minnesota Power and Light Co. Arrowhead Substation, Transformer, Duluth, Minnesota, August 4, 1972. Scale is ± 100 amps. from center scale. Transformer is GE, 3Ø autotransformer, core form, 230/115 kV grd. wye, delta tertiary, 100/133/157 MVA, OA/FA/FOA, 0.45% exciting current.

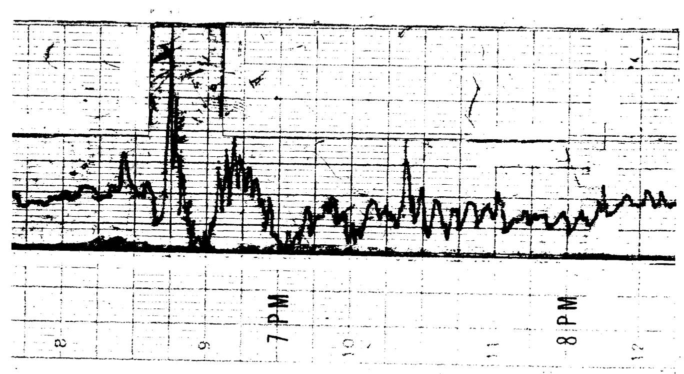

Fig. 3. SIC at Whitpain #1 transformer, Philadelphia Electric Company, Philadelphia, Pa. Scale is ± 100 amps. from center scale. Transformers are three Westinghouse single-phase autotransformers with delta tertiary, 500/230 kV grd. wye, 13.8 kV delta, 217 MVA each, 650 MVA total, average exciting current per phase is 0.441%.

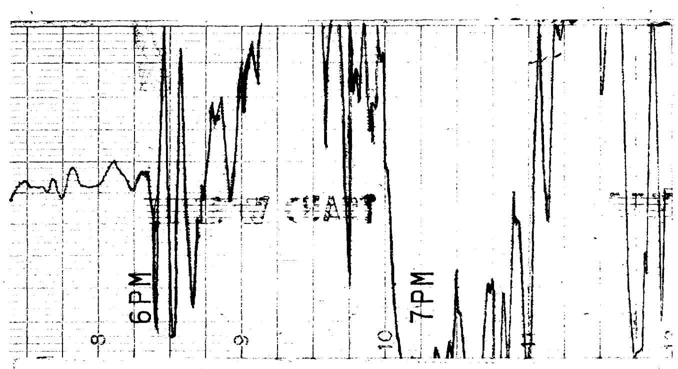

Fig. 4. SIC at Newfoundland and Laborador Power Commission, Corner Brook Transformer, Corner Brook, Newfoundland, August 4, 1972. Scale is ± 100 amperes from Center Scale. Transformer is Maloney Electric Co. of Canada, 3Ø, two winding, core form, 50 Hz, 69/6.6 kV and Wye/delta, 21/28 MVA.

POWER SYSTEM DISTURBANCES – QUALITATIVE

The actual power system disturbances that were reported during the August 4, 1972, geomagnetic storm are reported in Appendix 1. While a detailed quantitative analysis of the system disturbances is virtually impossible, a qualitative discussion of the various classes of disturbances may be helpful to an overall understanding.

The categories of disturbances reported include shifts in MVAR flow, shifts in MW flow, voltage fluctuations, frequency shift, relay operations, third-harmonic currents in transformer tertiary windings, and communication, telemetering, and supervisory alarm failures.

Many of the disturbance classes reported are due directly or indirectly to the presence of the SIC in transformer windings. With SIC in its windings, a transformer is subjected to simultaneous ac and dc excitation, resulting in half-cycle saturation of the core. Aside from attendant leakage flux problems within the transformer, the half-cycle saturation causes an increased transformer inductive VAR requirement, and an increase in harmonic generation by the transformer.

The increased transformer inductive VAR requirement directly accounts for much of the shift in VAR flow on the system. Every grounded-wye transformer in the affected system will contribute to this to some degree. The voltage magnitudes at the buses will be strongly affected by the VAR changes at the buses, and will thus influence VAR flow on other parts of the system through secondary effects. Variations in the system voltage profile will cause load demand in watts to vary, and this will contribute to shifts in MW flow on the system; the MW shifts are generally much less than the MVAR shifts, assuming no strategic circuit breaker openings. Frequency shifts can be related to the changes in MW demand and system losses, as compared to generation, over whatever system or interconnected systems area is strongly affected by the geomagnetic storm. The network complexities of interconnected power systems, system grounding particulars, and the variations in the response characteristics of transformers subjected to SIC make accurate calculation of these system disturbances due to SIC an impossibility.

The relay operations that were reported include transformer differential (with no harmonic restraint), generator field ground, generator time-overcurrent, undervoltage relays, and capacitor-bank neutral overcurrent. With the exception of the generator field ground relay, the remainder of the relay operations can be related to the increased VAR and harmonic generation of transformers subjected to SIC. It is difficult to associate the generator field ground relay operation with known effects from SIC.

The communication, telemetering, and supervisory alarm failures were due to fading in point-to-point radio or microwave systems. Metallic communication circuits, including coaxial cable systems, were interrupted or disturbed because of the earth-surface-potential accompanying the geomagnetic storm.

SYSTEM OPERATION

The system operating effects of the storm were more noticeable in northern latitudes and in igneous rock areas. In the regions where the electrical transmission system was extensive, the variations in MW, MVAR, voltage and frequency were generally not discernible from normal operating conditions – even though significant SIC and transformer tertiary currents were measured. This was typical in the East and Central United States. In the northern, igneous rock areas, where the transmission system is not as extensive, severe voltage dips were noticed along with significant VAR and some MW and frequency excursions. The areas that noticed the most significant variations were northern Minnesota, North Dakota, Manitoba, Newfoundland and portions of Ontario and Quebec. Newfoundland and eastern North Dakota seemed to have deviations that were far more severe than normal operating conditions.

The voltage collapsed down to 64% on the Grand Forks end of Manitoba-North Dakota interconnection. This would have been enough to cause a system breakup had it occurred during high North Dakota export levels with the 1972 transmission configuration.

REPORTED POWER SYSTEM DISTURBANCES

All responses that were obtained from a request for reports of operating disturbances are included in Appendix 1. Also included are a listing of those companies that reported no system operating disturbances noted.

All system operating disturbances are included, including the minor ones, so that the severity of the system disturbances in a particular geographical area can be correlated with the intensity of the geomagnetic field variations and geological considerations in some detail. Figure 5 is a map of North America, summarizing the points at which disturbances were reported on power systems.

Unless indicated otherwise, all of the system disturbances reported occurred at 2242 U.T. Samples of MVAR shift, MW shift, voltage fluctuation, and frequency shift are given in Figures 6 and 7.

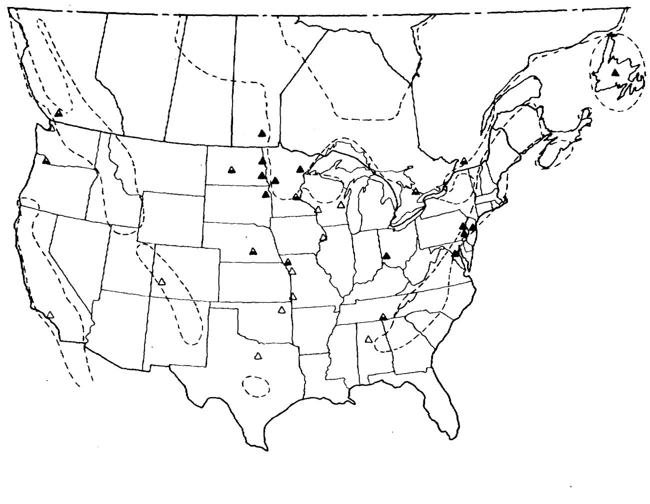

Fig. 5. Reported Power System Disturbances or SIC August 4, 1972. ▲ = *strong.* ▲ = *moderate.* Δ = *weak. Igneous Rock Areas outlined.*

CONCLUSIONS

A geomagnetic storm of K-8 intensity can produce disturbances in electric power systems over large geographical areas. The severity of the effects vary with latitude and igneous rock geology. The disturbances reported in this paper are typical, but might differ in specifics, for another K-8 storm. Indeed, power systems in certain geographical areas could experience effects equally as severe from a storm of lesser magnitude, such as a K-7 storm.

While this particular geomagnetic storm did not produce any widespread outages or major system stability problems, such potential exists for severe geomagnetic storms.

ACKNOWLEDGEMENTS

The authors wish to thank the individuals who gave of their time and made system operating and geomagnetic data available.

The authors express their appreciation to the Edison Electric Institute, which is sponsoring this joint research effort with the University of Minnesota and the General Electric Company, Schenectady, New York. Approximately thirty private electric utility companies are making important contributions through the purchase and installation of recording equipment, and the collection of data. Several governmental and Canadian electric power organizations are also contributing data and other information.

The authors also express their gratitude for the encouragement and guidance of the EEI Steering Committee for the Project: Chairman, J.M. Thorson, Jr., Northern States Power Co.; R.E. Armstrong, Consumers Power Co.; W.O. Uhl, Long Island Lighting Co.; and R.F.H. Wessel, Dayton Power and Light Co.

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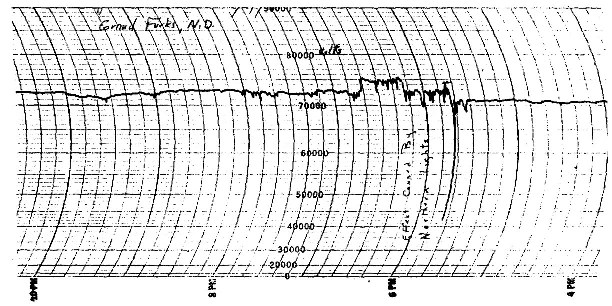

Fig. 6. Voltage Shift, Grand Forks, N.D.

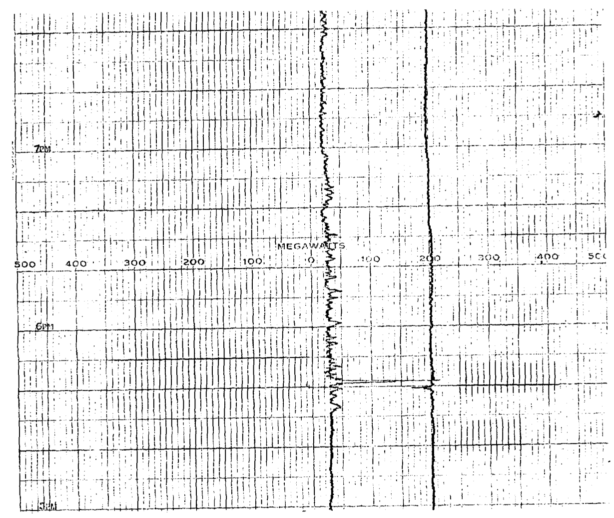

Fig. 7. MW (right) and MVAR (left) Shift Center – Fargo, N.D. 230 kV Line.

APPENDIX 1

SUMMARY OF GEOMAGNETIC STORM OF AUGUST 4, 1972

1. **Definitions**

Eastern United States and Canada are defined from eastern boundaries to 85° longitude.
Middle United States and Canada are defined from 85° to 105° longitude.
Western United States and Canada are defined from 105° longitude to western boundaries.

2. **No System Disturbances Noted**

2.1 **Eastern United States and Canada**

Atlantic City Electric Co.	Atlantic City, NJ
Baltimore Gas and Electric Co.	Baltimore, MD
Cincinnati Gas and Electric Co.	Cincinnati, OH
Dayton Power and Light Co.	Dayton, OH
Delmarva Power and Light Co.	Wilmington, DE
Detroit Edison Co.	Detroit, MI
Duke Power Co.	Charlotte, NC
Jersey Central Power and Light Co.	Morristown, NJ
Luzerne Electric Division-UGI	Philadelphia, PA
Metropolitan Edison Co.	Reading, PA
New Jersey Power and Light Co.	Morristown, NJ
Niagara Mohawk Power Corp.	Syracuse, NY
Northern Indiana Public Service Co.	Hammond, IN
Pennsylvania Electric Co.	Johnstown, PA
Virginia Electric and Power Co.	Richmond, VA

2.2 **Middle United States and Canada**

Central Illinois Light Co.	Peoria, IL
Central Louisiana Electric Co.	Alexandria, LA
City Water, Light and Power	Springfield, IL
Electric Reliability Councils of Texas	San Antonio, TX
Interstate Power Co.	Dubuque, IA
Kansas City Power and Light	Kansas City, MO
Kansas Gas and Electric Co.	Wichita, KS
Kansas Power and Light Co.	Topeka, KS
Louisiana Power and Light Co.	New Orleans, LA
Oklahoma Gas and Electric Power Co.	Oklahoma City, OK
Southwestern Electric Power Co.	Shreveport, LA
Texas Power and Light Co.	Dallas, TX
Union Electric Co.	St. Louis, MO
Western Farmers Electric Co-op	Anadarko, OK

2.3 **Western United States and Canada**

Arizona Public Service Co.	Phoenix, AZ
Bonneville Power Administration	Portland, OR
City of Anaheim	Anaheim, CA
City of Seattle	Seattle, WA
Department of Water Resources	Sacramento, CA
Idaho Power Co.	Boise, ID
Nevada Power Co.	Las Vegas, NV
Pacific Gas and Electric Co.	San Francisco, CA
Sierra Pacific Power Co.	Reno, NV
Southern California Edison Co.	Rosemead, CA
USBR-Lower Colorado	Phoenix, AZ
USBR-Lower Missouri	Denver, CO
USBR-Mid Pacific	Sacramento, CA
USBR-Pacific Northwest	Boise, ID
USBR-Southwest Region	Amarillo, TX
Utah Power and Light Co.	Salt Lake City, UT
Washington Water Power	Spokane, WA

3. Power System Disturbances Noted and/or SIC Recorded

3.1 Eastern United States and Canada

Dayton Power and Light Co., Dayton, Ohio

SIC of approximately 100 amperes peak in the neutral of a 345/22.8 kV, 640 MVA, Bank G1 transformer, at J.M. Stuart Station, at 1842 EDT. Varying magnitudes of SIC from 1700 to 2300 EDT.

Hydro-Quebec, Montreal, Quebec, Canada

MW variations of a few percent. Bersimis #2, on power-frequency control, had MW variation of 90%.

Significant variations of MVARS at all generating stations.

Voltage variations of 3.6% (735 kV sending end) to 5.7% (315 kV receiving end).

Shunt capacitor bank tripped off by overload protection at 18:52 EDT on August 4, 1972.

Many intermittent alarms caused by fading on microwave systems.

Loss of telemetering system of the La Gabelle generating station at 20:26 EDT on August 4, 1972.

Newfoundland and Labrador Power Commission, St. John's, Newfoundland, Canada

The Corner Brook transformer tripped on differential relay (IAC, no harmonic restraint) and was returned to service several times as follows:

8/4/72: 2012 – 2112; 2230 – 2243; 2332 – 2349 NST.

8/5/72: 0022 – 0032; 0131 – 0140; 1245 – 1812 NST.

Long Harbour Terminal tripped as above at the following times:

8/4/72: 2012 – 2152; 0022 – 0058 NST.

(Note: NST is 1½ hours ahead of CDT.)

False alarms on power line carrier circuits on August 5, 1972, at approximately 2210 hours NST.

SIC at Corner Brook started at about 20 amperes at 03/2330 NST and for the next five hours fluctuated between plus 100 to minus 100 amperes. It varied around 10 amperes until 04/1812 NST when excursions over 100 amperes, plus and minus, took place. This lasted until around 05/0500 when it dropped to half until 05/1000 when the chart ran out. At 04/1850 SIC was near 100 amperes and stayed at the same polarity for nearly 30 minutes.

Pennsylvania Power and Light Company, Allentown, Pennsylvania

Juniata – Peach Bottom 500 kV line 10 to 270 MVAR
Juniata – Peach Bottom 500 kV line 80 to 50 MW
Lackawanna – East Towanda 230 kV line 10 to 6 MVAR
Lackawanna – East Towanda 230 kV line 20 to 18 MW
Martins Creek – Portland 230 kV line 120 to 80 MW
Juniata – Alburtis 500 kV line 10 to 0 MVAR
Juniata – Alburtis 500 kV line 35 to 10 MW
Manor – Graceton, Conestone 230 kV line 0 to 38 to -32 MW
Bird Island – Mid Junction Hummelston 230 kV line 48 to 40 to 60 MW
Hosensack – Whitpain 230 kV line 24 to 20 MVAR

Juniata – sum of transformers #1 and #2 tertiary currents were 176 amperes RMS.

Philadelphia Electric Co., Philadelphia, Pennsylvania

SIC of 20 amperes in neutrals of both Whitpain substation transformers at 1652 EDT increasing to 40 amperes 1 hour later. At 1842 EDT SIC increased to 100+ amperes in Whitpain #1 and to 120 amperes estimated in Whitpain #3. Peach Bottom SIC peaked at 63 amperes. There was a spike of 40 amperes at 1925 EDT, Whitpain. SIC diminished to 20 amperes at 2000 EDT and stayed between 5-10 amperes until 2245 EDT when it rose to 30 amperes in a 30 minute cycle. Peach Bottom SIC followed Whitpain SIC closely at 60-70% of the Whitpain values.

Frequency exursion of 0.045 Hz.

Potomac Electric Power Co., Washington, D.C.

Frequency variation 59.98 to 60.03 Hz.

Public Service Electric and Gas Co., Newark, New Jersey

Branchburg – Ramapo 500 kV line 90 to 120 MVAR
Branchburg – Ramapo 500 kV line 90 to 110 MW
Branchburg – Alburtis 500 kV line 300 to 280 MVAR
Branchburg – Alburtis 500 kV line 610 to 590 to 630 MW
Branchburg – Whitpain 500 kV line 40 to 60 MVAR
Branchburg – Whitpain 500 kV line 220 to 270 MW
Linden – Goethals 230 kV line 30 to 0 to 80 MVAR
Linden – Goethals 230 kV line 40 to 50 MW
Pleasant Valley – Buckingham 230 kV line 10 to 20 MVAR
Pleasant Valley – Buckingham 230 kV line 20 to 30 MW
New Freedom – Monroe 230 kV line 80 to 60 MVAR
Roseland – Montville 230 kV line 10 to 70 MVAR
Lawrence Switch (connected to Branchburg) 6 to 14 MVAR
Trenton Switch (connected to Branchburg) 23 to 31 to 35 MVAR

Total generation change 2900 to 3080 MW.
Total generation change 1100 to 1500 MVAR.

SIC at Branchburg started at about 10 amperes at 1640 EDT and peaked 80 amperes at 1842 EDT, dropped back to 5 amperes around 1855 EDT, spiked occasionally to 10 amperes and peaked again at 20 amperes at 2050 EDT and then subsided rapidly.

Transformer oil gas analysis from oil samples taken 7-17-72 and 8-16-72 showed no significant changes.

3.2 Middle United States and Canada

Board of Public Utilities, Kansas City, Kansas

System load dropped from 272 MW to 267 MW, then recovered to 270 MW.
System generation voltage from 1.40 kV to 1.39 kV to 1.40 kV.
System frequency from 60.00 to 59.99 to 60.015 Hz.

Dairyland Power Cooperative, La Crosse, Wisconsin

Alma 69 kV bus 120.5 to 119 V.

Empire District Electric Co., Joplin, Missouri

200 MW generator 10 MVAR to 0; other succeeding fluctuations in MVARs of lesser amounts.

Iowa-Illinois Gas and Electric Co., Davenport, Iowa

Hills Station 166-164 kV.
Hills Station 363-355 kV.
Frequency change 59.985 to 60.03 Hz.

Manitoba Hydro Co., Winnipeg, Manitoba, Canada

USA Tie Line (La Verendrye) 120 to 164 to 44 MW
USA Tie Line (La Verendrye) +25 to -100 MVARS
Grand Rapids 230 kV bus 295 to 336 to 295 to 340 MW
Grand Rapids 230 kV bus 40 to 250 MVARS
Grand Rapids 230 kV bus 237 to 220 to 247 kV
La Verendrye 115 kV bus 114 to 96 to 116 kV
Morden 115 kV bus 112 to 96 kV
Parkdale 115 kV bus 113 to 96 kV
Selkirk 115 kV bus 116 to 100 kV
System Voltage 111.0 to 90.0 kV

At La Verendrye, SIC > ± 100 amps. in neutral of 230/115 kV transformer #2.
At Grand Rapids, SIC ~ ± 100 amps. in neutral of 13.8/230 kV transformer #1.

System Frequency 60.00 to 59.95 to 60.08 Hz

Seven Sisters Unit #2 (25 MW) tripped by generator field ground and overcurrent time A and C phase relays.
Slave Falls Unit #3 (9 MW) tripped by undervoltage relay.
Grand Rapids reported phase unbalanced annunciations on Units #1, 2, 3, and 4.
Kettle Rapids reported phase unbalance annunciations on Units #2 and 5 (R24G line).
Grand Rapids and Kettle Units went to maximum VAR output at 17:40 CDT, August 4, 1972.
Load Dispatch requested all generator units to maximum voltage boost at 1755 CDT, hoping to prevent loss of additional generator units.
No transformers tripped out by differential relay operations.

Minnesota Power and Light Co., Duluth, Minnesota

Aurora Station 30 to 87 MW
Clay Boswell gen. station 25 to 74 MVAR
Blackberry 230 kV substation 40 to 100 to 50 MVAR
Blanchard 34.5 kV bus 36 to 30 kV
Boswell 115 kV bus 122 to 116 kV
Hibbing 115 kV bus 120 to 112 kV
Hibbard 115 kV bus 115 to 105 kV
Thomson 46 kV bus 46.4 to 43.2 kV
Pillager 34.5 kV bus 36 to 30 kV
Knife Falls Hydro Station 2.3 to 2.2 kV
Little Falls Hydro Station 2.4 to 2.08 kV

Riverton Substation: 400 amperes of third-harmonic current in auto-transformer tertiary.
Blackberry Substation: 300 amperes of third-harmonic current in auto-transformer tertiary.
Noticed no phase current unbalance or transformer neutral current.
Arrowhead Substation, Duluth, Minnesota: SIC first went to 22 amperes at 1555 CDT, 60 amperes at 1742 CDT and dropped exponentially to 20 amperes at 1845 CDT, then varied from 5 to 20 amperes until 2100 CDT.

Minnkota Power Cooperative, Grand Forks, North Dakota

Winnipeg – Grand Forks 230 kV 70 to 140 to -200 MW
Center – Fargo 230 kV line 200 to 170 to 200 MW
Center – Fargo 230 kV line 30 to 210 to 30 MVAR
Stanton – Center 230 kV line 130 to 115 to 130 MW
Stanton – Center 230 kV line 40 to 120 to 50 MVAR
Center – Hesket 230 kV line 170 to 176 to 170 MW
Center – Hesket 230 kV line 10 to 100 to 10 MVAR
Grand Forks 69 kV bus 71 to 42 to 75 kV
Maple Lake, Minn. (Cabin) 123 to 60 to 150 V
Prairie 230 kV bus 234 to 150 to 238 kV
Maple River 230 kV bus 234 to 150 to 238 kV
Prairie 230/115 kV bank oscillographs showed high harmonics on polarizing current and voltage.

Montana – Dakota Utilities, Bismarck, North Dakota

Ellendale – Forman 230 kV line 138 to 133 kV
Ellendale 115 kV bus 120 to 96 kV
Glenham 115 kV bus 116 to 105 kV
Hesket 230 kV bus 225 to 209 kV
Bismarck frequency 60.000 to 60.075 Hz.

Ellendale oscillograph shows spiked phase currents.

Nebraska Public Power District, Hastings, Nebraska

Grand Island – Ft. Thompson 345 kV line 270 to 255 to 270 to 255 to 290 MW
Grand Island – Ft. Thompson 345 kV line 25 to 90 MVAR
Wagener – Ft. Calhoun 345 kV line 23 to 33 MW
Cooper – St. Joseph 345 kV line 15 to 45 to 15 MW
Columbus – Ft. Randall 230 kV line 115 to 32 to 115 MW
Other 115, 161, 230, and 345 kV lines showed similar shifts.

Hastings 115 kV bus dropped 3 kV.
System load indicated from 720 to 700 MW.
Sheldon Generator from 181 to 176 MW.
Area net interchange from 300 to 286 to 308 MW.
Area control error 30 MW for 30 seconds.
System frequency from 60.00 to 59.98 to 60.03 Hz.

Northern States Power Co., Minneapolis, Minnesota

King – Eau Claire 345 kV line 116 to 92 MW
Red Rock – Adams 345 kV line 0 to 30 MW
Red Rock – Adams 345 kV line 90 to 100 MVAR
Lakefield – Parkers Lake 345 kV line 50 to 60 MW
Lakefield – Parkers Lake 345 kV line 110 to 50 MVAR
Eau Claire – Rocky Run 345 kV line 50 to 80 MW
Red Rock – Arrowhead 230 kV line 50 to 70 MW
Red Rock – Arrowhead 230 kV line 0 to 50 MVAR
Riverton – Monticello 230 kV line 40 to 20 MW
Fargo – Cass Co. 115 kV line #1 52 to 36 MW
Fargo – Cass Co. 115 kV line #2 24 to 12 MW
Maple River – Red River 115 kV line 45 to 40 MW
USBR – NSP Grand Forks 69 kV 12 to 15 MW
Red Rock 345 kV bus 349 to 345 kV
Red Rock 115 kV bus 119 to 118 kV
Grand Forks 69 kV bus 118 to 90 V
Cass Co. 23 kV bus 25 to 18 kV
Minneapolis Frequency 60.00 to 60.02 Hz.
Fargo, N.D. Frequency 60.00 to 60.015 Hz.

Glenwood, Minn. had an IJD differential relay trip on a 3-2.5 MVA 69-4 kV wye-wye Bank. (3-.5 MVA wye-delta ground banks.) No harmonic restraints on relays.
Fargo, N.D. Dispatch Center emergency generator ran 5 minutes.

Otter Tail Power Co., Fergus Falls, Minnesota

Hoot Lake 115 kV bus voltage dropped 18%.
Bemidji 41.6 kV voltage dropped 22%.
Crookston 41.6 kV voltage dropped 33%.
Ortonville bus voltage dropped 13%.
Devils Lake, North Dakota Plant voltage dropped 11%.
41.6 kV Breaker Operation in Substation of Cooperative Power Association. Under voltage relay target.
Outage in Langdon, North Dakota area due to a breaker operation on Minnkota 69 kV system – outage longer than normal due to communications interruptions by geomagnetic storm. Supervisory control misoperation.
Numerous telemetering failures and supervisory alarms.
N.D. N-S Guide Line Flows 464 MW
N.D. N-S Actual Exports 660 MW

Ontario Hydro, Toronto, Ontario, Canada

Ontario-Michigan interconnection 540 to 480 MW
Ontario-New York State interconnection 310 to 280 MW
Pinard 500 kV bus 2% voltage change
Richview 230 kV bus 236 to 234 kV (1%)
Essa 115 kV bus 4% voltage change
Lakehead 115 kV bus 120 to 118 kV (2%)
Atikokan 115 kV bus 119 to 115 kV (4%)
Kenora 115 kV bus 125 to 115 kV (8%)
System frequency 60.00 to 60.03 Hz.
System load increase 150 MW

Public Service of Oklahoma, Tulsa, Oklahoma

345 kV line: less than 10 MW and 10 MVAR shift
System voltage 341 to 339 kV
System frequency 59.98 to 60.03 Hz.

Unexplained supervisory alarm-station annunciator panel showed transformer neutral relay light on and low gas light on – alarms were reset.

St. Joseph Light and Power Company, St. Joseph, Missouri

345 kV line: increase north to south of 45 MW
345 kV line: increase south to north of 15 MVAR

Southern Company System, Birmingham, Alabama

System frequency 59.99 to 60.03 Hz.

No other unusual flows or operations noted.

Tennessee Valley Authority, Chattanooga, Tennessee

Paddy's Run interconnection showed a shift of 20 MW.
Area control error chart showed 100 MW overgeneration.
Frequency went from 59.99 to 60.02 Hz., indicating overgeneration of 1 GW.
Secondary voltage in neutral of 161 kV capacitor bank was high and off scale at 10+ volts.
Transformer noise level above normal in Tupelo, Mississippi.
Third-order harmonics in transformer neutrals.

Texas Electric Service, Fort Worth, Texas

Maximum SIC 4 amps.

U.S. Bureau of Reclamation, Watertown, South Dakota

Granite Falls-Black Dog 230 kV line 5 to 45 MVAR
Fargo-Grand Forks 115 kV line 12 to 0 to 20 MW
Fargo-Grand Forks 115 kV line 5 to -20 to 15 MVAR
Watertown 230 kV bus 235 to 205 kV
Grand Forks 115 kV bus 115 to 64 to 118 kV
Watertown 69 kV bus 71 to 58 kV

Jamestown oscillograph recorded high third-harmonic polarizing current.
The Watertown oscillograph has triggered hundreds of times during magnetic storms since the 1950's.

Wisconsin-Michigan Power Company, Appleton, Wisconsin

Forest Junction net interchange 15 to 24 to 17 MVAR
North Appleton to Ellington-Butte Des Morts 175 to 191 to 177 MVAR

3.3 Western United States and Canada

Bonneville Power Administration, Vancouver, Washington

SIC recorder showed 25 amps peak with change rates of 2.5 to 3 amps per second.
Initial excursions of 3 amps SIC began at 1335 PDT, 7 amps at 1430 PDT and 25 amps at 1542 PDT. This diminished almost exponentially back to 3 amps SIC at 2100 PDT. The major portion of the disturbance was over around 1930 PDT.
No change in gas analysis data from oil samples taken after the geomagnetic storm.

City of Los Angeles, Los Angeles, California

10 MW and 10 MVAR excursion at Sylmar between City of Los Angeles and Southern California Edison but other excursions at other times were greater.

Puget Sound Power and Light, Redmond, Washington

A 40 MVAR 115 kV capacitor bank at White River Substation relayed off on neutral overcurrent at 1545 PDT. Six others, all the same, had no operations.

USBR – Upper Colorado, Montrose, Colorado

5 MVAR shift.
236 to 234 kV.

For Combined Discussion see page 1038